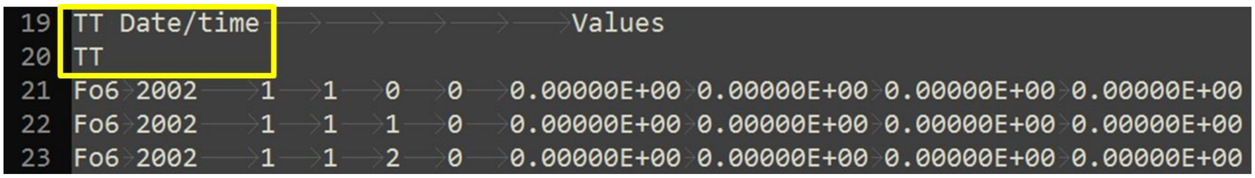
Appendix D

Technical Notes

Technical Note 1

Formatting the External Land Use Simulation

When developing a *SUSTAIN* application using the external simulation option, runoff and pollutant loading are input for each hydrologic response unit as a boundary condition from an external ASCII file. Using the external ASCII file format provides the flexibility for any existing rainfall-runoff, watershed, or other model to be used within the optimization framework as long as the model output time series can be pre-processed into a standard format. This common format includes general temporal information (date, time, etc.) as well as surface runoff, groundwater recharge, and pollutant loading. SUSTAIN assumes each time series represents contributions from one acre. Users have some freedom to format external time series as either space or tab delimited; however, the reference keyword “Date/time” must be specified followed by a blank line for the system which is presented in Figure 1. All file content before this keyword is considered as header information and is not used in any way by the system.



```
19 TT Date/time                Values
20 TT
21 Fo6 2002  1  1  0  0  0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
22 Fo6 2002  1  1  1  0  0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
23 Fo6 2002  1  1  2  0  0.00000E+00 0.00000E+00 0.00000E+00 0.00000E+00
```

Figure 1. Example format of external time series files showing the required reference keyword structure.

Users may include meaningful header information in any external time series file prior to the line which includes the text “Date/time”. When reading in external time series files, *SUSTIAN* searches for this text as a reference point. This line, and the one following it (shown in the yellow box in Figure 1), will be skipped and any reaming lines in the file will be read as input. Input lines may be tab or space delimited. An example of the external time series format is presented below in Figure 2.

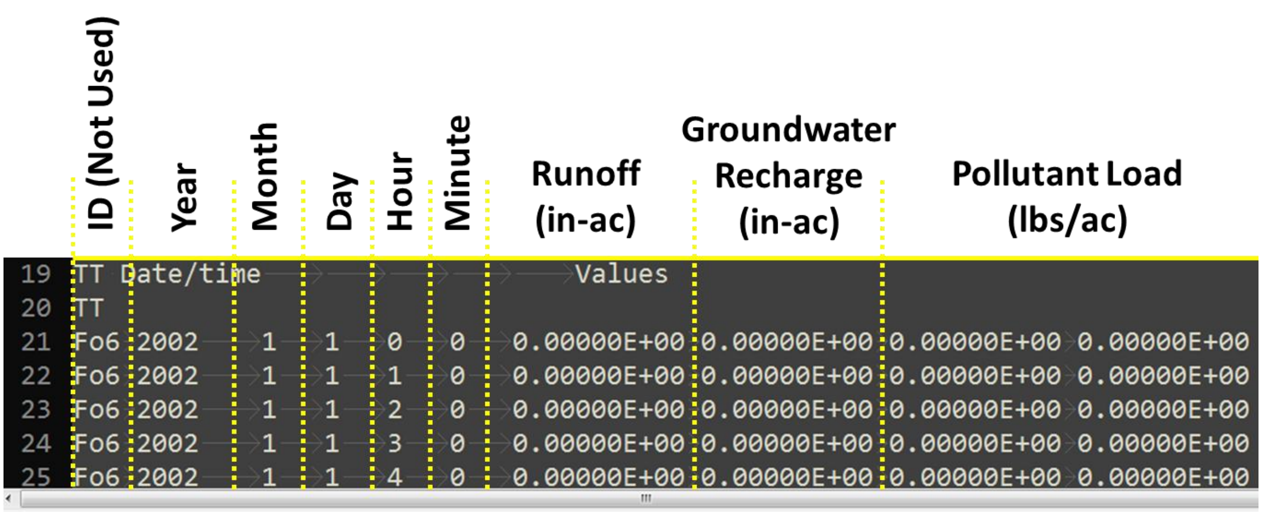


Figure 2. Example format of external time series files.

The first column represents a station identification number or other user specified identification that is not used by *SUSTAIN*. The following five columns represent the year, month, day, hour, and minute respectively. The seventh column represents surface runoff with units of inches per time step. The eighth column represents groundwater recharge with units of inches per time step. This column is required of all external time series used in *SUSTAIN*; however, it is only used if aquifer simulation is used in *SUSTAIN*. A placeholder value of 0 can be entered for all time steps if the aquifer feature will not be used. Subsequent columns are used to represent corresponding pollutant loading with units of pounds per acre per time step. If the mass units are given as something other than pounds, an optional multiplier can be entered in *SUSTAIN* when configuring the pollutant definitions to convert all units to pounds. *SUSTAIN* requires at least one pollutant to be included in the external time series file even if the study objectives are not water quality related. A placeholder value of 0 can be entered in that case.

Technical Note 2

The Land Use Look-up Table

The land use lookup table is used within the ArcGIS environment for setting up a new *SUSTAIN* project. This table is used to map values or codes in the land use raster to meaningful descriptions of each land use category. The lookup table should be saved in a standard DBF format (creatable in Microsoft Excel 2003) for use in ArcGIS. An example of the land use lookup table as viewed through ArcCatalog is shown below as Figure 3.

Contents | Preview | Description

OBJECTID *	LUCODE	LUNAME	LUDesc
1	110	ESR-Pervious	Estate Residential-Pervious
2	111	ESR-Bldg	Estate Residential-Bldg
3	112	ESR-Pklot	Estate Residential-Pklot
4	113	ESR-Road	Estate Residential-Road
5	130	HDR-Pervious	High Density Residential-Pervious
6	131	HDR-Bldg	High Density Residential-Bldg
7	132	HDR-Pklot	High Density Residential-Pklot
8	133	HDR-Road	High Density Residential-Road
9	170	LDR-Pervious	Low Density Residential-Pervious
10	171	LDR-Bldg	Low Density Residential-Bldg
11	172	LDR-Pklot	Low Density Residential-Pklot
12	200	OS-Pervious	Open Space-Pervious
13	210	TRANS-Pervious	Transportation-Pervious
14	212	TRANS-Pklot	Transportation-Pklot
15	213	TRANS-Road	Transportation-Road
16	214	TRANS-PervRdMedian	Transportation-PervRdMedian

Figure 3. Example land use lookup table.

There are two critical fields that must exist in each lookup table that *SUSTAIN* will search for during setup (1) LUCODE, and (2) LUNAME. The LUCODE field must be specified as type ‘Long’ or ‘Double’ and should correspond to values in the land use raster. The LUNAME field must be specified as type ‘String’ and should not contain any spaces. In fact, it is good practice to eliminate spaces and other special characters from all naming conventions used in *SUSTAIN* projects. It is critical to ensure all values in the land use raster exist in the land use lookup table.

Technical Note 3

Editing the SUSTAIN Input File

SUSTAIN's ArcGIS interface provides the user with a powerful data management framework capable of performing complex spatial calculations. These considerations of complex information management and spatial data analysis make GIS-based systems a natural platform for *SUSTAIN.* The database structure of ArcGIS maintains all the records of BMP properties, synthesizes the spatial data related to land use and subwatershed areas, and writes a validated input file before running the *SUSTAIN* model.

When the model setup phase is completed in ArcGIS, an ASCII input file is written with a *.inp extension which organizes the fully compiled model, including tabulated subwatershed land use distributions, BMP definitions, and optimization controls. This input file is used to run the *SUSTAIN* model. The input file is divided into numbered sections, or cards, as the primary organizational structure for saving similar data records. For instance, Card 710 specifies the land use definitions that were derived from the land use raster in ArcGIS. Each type of land use that falls within one of the model subwatersheds will have a record in Card 710 which provides the land use name and, if the external land use simulation option is used, specifies the time series file that represents each land use.

A modeler is able to edit this ASCII input file directly using any standard text editor before running the model; however, while direct modification of the input file may provide some desired flexibility, it also must be approached with caution. There are interdependencies between some input cards. For example, Card 715 lists the initial BMP definitions. Each BMP listed in Card 715 (except junctions and conduits) must also have a corresponding record in Card 725 (or 735), 730, 740, 745, 747, 765, 766, 767, 770, 775, 780, 785, 786, and 805 as these cards, in aggregate, store all the required properties of a BMP and its related processes. Additionally, each BMP would need a record in Card 790 if it received runoff directly from the land and also in Card 795 to define its position in the routing network. Optional BMP records could also exist in Card 723 if simulation of a pump is required or Card 810 and 815 if optimization is performed. In circumstances where a BMP is added outside of the ArcGIS interface via direct modification of the input file, the modeler must ensure model continuity in that subsequent records are properly added in all required input cards.

These record interdependencies are handled through database processes in ArcGIS and updated automatically when revision are made through the SUSTAIN interface. Once manual revisions are made to an input file, the modeler assumes responsibility for validating and maintaining all model inputs; however, it is recommended that modelers review the input files in a text editor for more familiarity with the model as some additional documentation is provided in the card headings. A complete list of all cards incorporated in the *SUSTAIN* input file structure is presented in Table 1.

It is also important to note that modifications to the input file will no longer be reflected in the ArcGIS project that was used to derive the initial input file.

Technical Note 3

Editing the SUSTAIN Input File

Table 1. Description of *SUSTAIN* input file structure

Input card number	Input card title
700	Model Controls
705	Pollutant Definition
710	Land Use Definition
712	Aquifer Information
713	Aquifer Pollutant Background Concentration
715	BMP Site Information
720	Point Source Definition
721	Tier-1 Watershed Outlets Definition
722	Tier-1 Watershed Timeseries Definition
723	Pump Curve
725	CLASS-A BMP Site Parameters
730	Cistern Control Water Release Curve
735	CLASS-B BMP Site Dimension Groups
740	BMP Site Bottom Soil/Vegetation Characteristics
745	BMP Site Holtan Growth Index
747	BMP Site Initial Moisture Content
750	Class-C Conduit Parameters
755	Class C Conduit Cross Sections
760	Irregular Cross Sections
761	Buffer Strip BMP Parameters
762	Area BMP Parameters
765	BMP Site Pollutant Decay/Loss rates
766	Pollutant K' values
767	Pollutant C* values
770	BMP Underdrain Pollutant Percent Removal
775	Sediment General Parameters
780	Sand Transport Parameters
785	Silt Transport Parameters
786	Clay Transport Parameters
790	Land to BMP Routing Network
795	BMP Site Routing Network
800	Optimization Controls
805	BMP Cost Functions
810	BMP Site Adjustable Parameters
815	Assessment Point and Evaluation Factor

Technical Note 4

Background Infiltration Rate Sensitivity Analysis

Sensitivity analysis has shown that the background infiltration rate is one of the most sensitive BMP parameters in *SUSTAIN* (Shoemaker et al. 2012). As part of the Chagrin River watershed pilot, this sensitivity was tested. The cost-effectiveness curve is based on assumptions of pervious runoff time series and BMP infiltration rates consistent with HSG-C soils. A reduction in infiltration rates from HSG-C to HSG-D can dramatically impact the results of the optimization model. To test the sensitivity of the soil group assumption, two parallel optimization models were developed using runoff boundary conditions and BMP parameters consistent with both HSG-C and HSG-D site conditions. Background infiltration rates for HSG-D were set at 0.08 inch per hour consistent with parameterization of soil conditions in the Grand River (lower) Watershed TMDL model (Tetra Tech 2011) which is located adjacent to the Chagrin River watershed.

The two models each generate unique cost-effectiveness curves which, when super-imposed as a single plot, produce cost-effectiveness bands that capture the uncertainty inherent in the model assumptions and bracket the expected runoff response to green infrastructure practices. Five unique solutions (points on the cost-effectiveness curve) were selected for comparison. The results of this sensitivity analysis comparing HSG-C and HSG-D assumptions are presented in Figure 4 and Table 2.

Table 2. Change in annual average flow reduction for selected solutions assuming HSG-C and HSG-D boundary conditions, Chagrin River watershed pilot

	Cost (million $)	HSG-C annual flow reduction (%)	HSG-D annual flow reduction (%)
Solution 1	0.53	10.5	9.4
Solution 2	1.15	29.5	25.7
Solution 3	3.30	52.0	48.1
Solution 4	4.61	60.5	56.5
Solution 5	6.21	69.2	65.1
Solution 6	11.13	80.3	76.6

Technical Note 4

Background Infiltration Rate Sensitivity Analysis

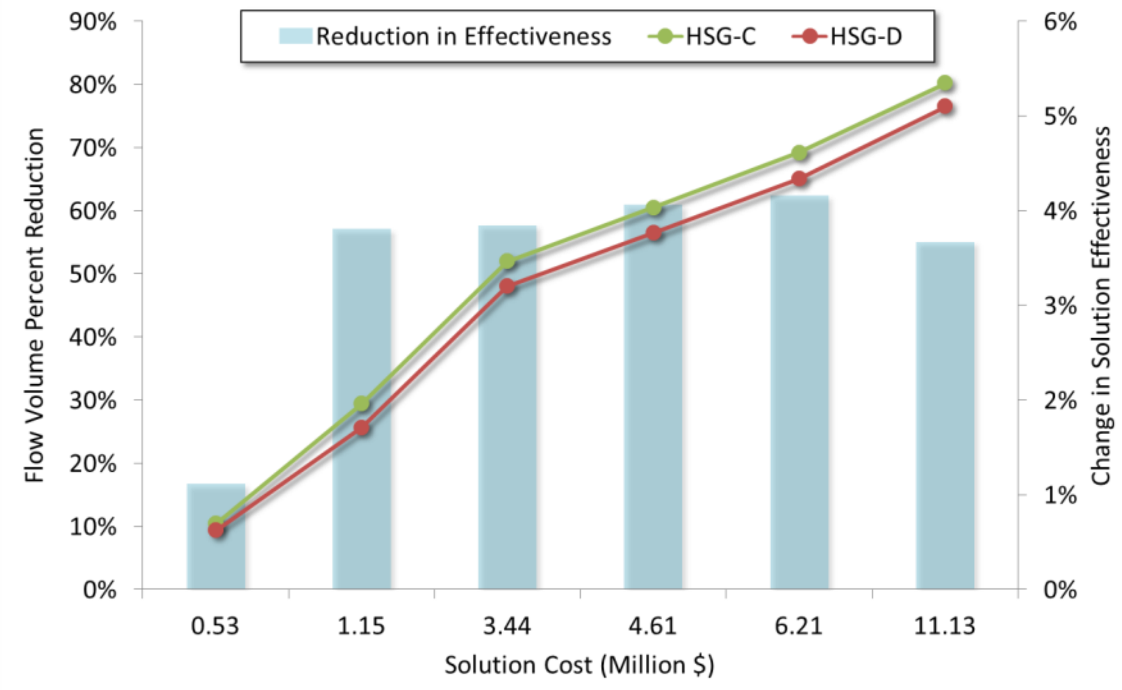


Figure 4. Comparison of selected solutions assuming HSG-C and HSG-D boundary conditions, Salt Creek watershed pilot.

As expected, the sensitivity analysis presented in Figure 4 shows that assumptions regarding soil properties can produce noticeable differences in BMP performance even when comparing HSG-C and D. In this case the pervious runoff time series and BMP infiltration rates were changed from representing HSG-C at 0.1 inch per hour to representing HSG-D at 0.08 inch per hour. A 0.02 inch per hour decrease in background infiltration rates produced a 1.1 percent to 4.2 percent decrease in BMP performance with regard to annual average flow volume reduction. Note that even though the model showed only a 4.2% change in BMP effectiveness across the watershed, the change in infiltration rates was fairly small. In many applications the degree of uncertainty will be higher. Thorough calibration against observed data or validation with site-specific data can help highlight or limit the influence of unknown model variables. The impact of assumptions are important to understand when performing any type of modeling; however, they becomes especially important within the *SUSTAIN* optimization framework when evaluation focuses on the trade-off between BMP performance and cost as a step towards planning and implementing stormwater capital infrastructure.

Technical Note 5

Catchment Configuration Sensitivity Analysis

SUSTAIN uses modeled unit-area hydrographs by land use to represent BMP boundary conditions, but those models have different assumptions for how the time series are derived. SWMM uses a catchment approach; therefore, physical configuration influences runoff and associated pollutant responses. There are four key factors that are used to define the configuration of a catchment in the model: (1) size, (2) slope, (3) shape, and (4) surface cover. Various combinations of those factors working together are manifested differently in terms of runoff volume, peak flow, time of concentration, and associated pollutant fate and transport. After setting up and calibrating SWMM using conventional methodology as part of the Duluth Area pilot study, an experiment was designed to test the sensitivity of those four factors on the calibrated model responses. Catchment size was varied across five orders of magnitude between 0.1 acres and 1,000 acres. All model results were normalized to a unit-acre basis for comparison between runs. Slope was varied between 1 percent and 10 percent, with 5 percent as a midpoint value. Catchment shape (i.e. length-to-width ratio) was varied between 0.25 and 4. Surface cover was modeled as forest, grass, 100 percent impervious, or mixed (50 percent impervious routed to 50 percent pervious). Altogether, there were 180 possible combinations of the individual catchment variables. Figure 5 illustrates the experimental design for this analysis.

A SWMM model (using the internal SWMM engine in *SUSTAIN*) was configured to run the 180 unique combinations of size, slope, shape, and surface. Nine years of Stage 3 NEXRAD radar-estimated hourly precipitation data were used for the runs, assuming wet and dry time steps of 15 minutes each. Other meteorological time series (daily minimum and maximum air temperature, and average daily wind speed) from the Duluth International Airport Surface Airways station (WBAN 14913) were also applied in the model. Daily evaporation was computed using the Penman-pan method with data from the airport station. Snowfall and snowmelt was simulated using standard dry and wet period methods used in SWMM 5, and the Green-Ampt method was used for infiltration on pervious land.

Sensitivity analysis results for all unique combinations were either normalized and/or converted to standard units for comparison. Figure 6 is a plot of annual average runoff volume in inches per year as a function of catchment configuration (expressed as 180 combinations of size, slope, shape, and surface factors). The blue-white-red color gradient shows the relative magnitude of runoff from low to high. The four highlighted boxes on the spectrum are the calibrated factor combinations for reference purposes. On the basis of GIS assessment, developed land was calibrated assuming flatter and longer catchments (5 percent slope and 4 for L/W ratio), while forest was calibrated using a steeper/shorter configuration (10 percent slope and 0.25 L/W ratio). Figure 6 through Figure 11 show similar plots for runoff coefficient, peak flow, infiltration, evaporation, and sediment load, respectively.

Technical Note 5

Catchment Configuration Sensitivity Analysis

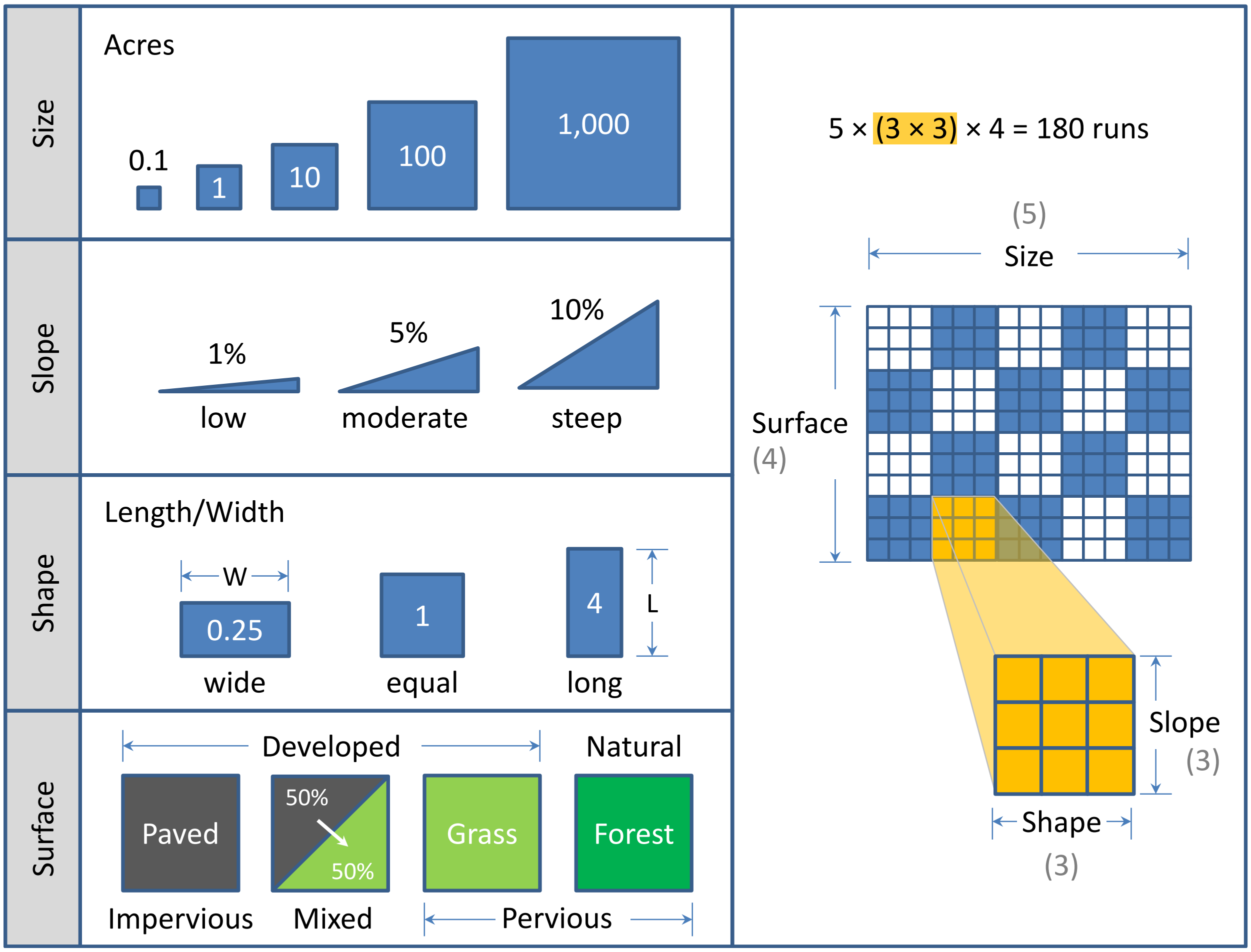


Figure 5. Experimental design to test the sensitivity of SWMM catchment configurations.

Technical Note 5

Catchment Configuration Sensitivity Analysis

Runoff (in./yr)

Calibrated | Low | Medium | High

Surface	Size (acres) →	0.1			1			10			100			1,000			Slope
	Shape L/W →	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	
Forest		1.2	1.1	0.9	0.9	0.8	0.6	0.7	0.5	0.4	0.4	0.3	0.2	0.2	0.1	0.1	1%
Forest		1.4	1.3	1.1	1.1	1.0	0.8	0.8	0.7	0.5	0.6	0.4	0.3	0.3	0.2	0.1	5%
Forest		1.5	1.4	1.2	1.2	1.1	0.9	0.9	0.8	0.6	0.7	0.5	0.4	0.4	0.3	0.2	10%
Grass		4.0	3.5	3.0	3.2	2.6	2.1	2.3	1.8	1.3	1.5	1.1	0.8	0.9	0.6	0.4	1%
Grass		4.4	4.0	3.6	3.7	3.3	2.7	2.9	2.4	1.9	2.0	1.6	1.2	1.3	0.9	0.6	5%
Grass		4.5	4.2	3.8	4.0	3.5	3.0	3.2	2.6	2.1	2.3	1.8	1.3	1.5	1.1	0.8	10%
Mixed		8.3	7.8	7.0	7.3	6.5	5.6	5.9	4.9	3.9	4.2	3.3	2.4	2.7	1.9	1.2	1%
Mixed		8.8	8.4	7.9	8.1	7.4	6.6	6.9	6.0	5.1	5.4	4.4	3.4	3.7	2.8	2.0	5%
Mixed		8.9	8.6	8.2	8.3	7.8	7.0	7.3	6.5	5.6	5.9	4.9	3.9	4.2	3.3	2.4	10%
Paved		20	20	20	20	20	19	19	19	18	18	18	17	17	16	14	1%
Paved		20	20	20	20	20	20	20	19	19	19	19	18	18	17	16	5%
Paved		21	20	20	20	20	20	20	20	19	19	19	18	18	18	17	10%

Figure 6. Annual average runoff as a function of SWMM catchment configuration.

Runoff Coefficient

Calibrated | Low | Medium | High

Surface	Size (acres) →	0.1			1			10			100			1,000			Slope
	Shape L/W →	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	
Forest		0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.00	0.00	1%
Forest		0.05	0.05	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.01	0.01	0.01	0.01	5%
Forest		0.05	0.05	0.04	0.04	0.04	0.03	0.03	0.03	0.02	0.02	0.02	0.01	0.01	0.01	0.01	10%
Grass		0.14	0.13	0.11	0.11	0.09	0.08	0.08	0.06	0.05	0.05	0.04	0.03	0.03	0.02	0.01	1%
Grass		0.16	0.14	0.13	0.13	0.12	0.10	0.10	0.09	0.07	0.07	0.06	0.04	0.05	0.03	0.02	5%
Grass		0.16	0.15	0.14	0.14	0.13	0.11	0.11	0.09	0.08	0.08	0.06	0.05	0.05	0.04	0.03	10%
Mixed		0.30	0.28	0.25	0.26	0.23	0.20	0.21	0.18	0.14	0.15	0.12	0.09	0.10	0.07	0.04	1%
Mixed		0.31	0.30	0.28	0.29	0.27	0.24	0.25	0.22	0.18	0.19	0.16	0.12	0.13	0.10	0.07	5%
Mixed		0.32	0.31	0.29	0.30	0.28	0.25	0.26	0.23	0.20	0.21	0.18	0.14	0.15	0.12	0.09	10%
Paved		0.72	0.72	0.71	0.71	0.70	0.68	0.69	0.67	0.65	0.66	0.63	0.59	0.60	0.56	0.52	1%
Paved		0.73	0.73	0.72	0.72	0.71	0.70	0.71	0.69	0.68	0.68	0.66	0.63	0.64	0.61	0.57	5%
Paved		0.73	0.73	0.72	0.72	0.72	0.71	0.71	0.70	0.68	0.69	0.67	0.65	0.66	0.63	0.59	10%

Figure 7. Annual average runoff coefficient as a function of SWMM catchment configuration.

Technical Note 5
Catchment Configuration Sensitivity Analysis

Peak Flow (in./hr)

Calibrated Low Medium High

Surface	Size (acres)	0.1			1			10			100			1,000			Slope
	Shape L/W	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	
Forest		1.4	1.3	1.0	1.1	0.8	0.6	0.6	0.4	0.2	0.3	0.2	0.1	0.1	0.1	0.0	1%
Forest		1.5	1.4	1.3	1.3	1.2	0.9	1.0	0.7	0.4	0.5	0.3	0.2	0.2	0.1	0.1	5%
Forest		1.6	1.4	1.3	1.3	1.2	1.0	1.1	0.8	0.6	0.6	0.4	0.2	0.3	0.2	0.1	10%
Grass		1.6	1.5	1.4	1.4	1.3	1.0	1.1	0.8	0.5	0.6	0.4	0.2	0.3	0.2	0.1	1%
Grass		1.7	1.6	1.5	1.5	1.4	1.3	1.3	1.2	0.9	1.0	0.7	0.4	0.5	0.3	0.2	5%
Grass		1.7	1.7	1.6	1.6	1.4	1.4	1.4	1.3	1.0	1.1	0.8	0.5	0.6	0.4	0.2	10%
Mixed		1.7	1.7	1.6	1.6	1.5	1.4	1.4	1.3	1.0	1.1	0.8	0.5	0.6	0.3	0.2	1%
Mixed		1.7	1.7	1.7	1.7	1.6	1.5	1.5	1.4	1.3	1.4	1.1	0.8	0.9	0.6	0.4	5%
Mixed		1.7	1.7	1.7	1.7	1.6	1.5	1.6	1.5	1.4	1.4	1.3	1.0	1.1	0.8	0.5	10%
Paved		1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.5	1.5	1.4	1.3	1.3	1.1	0.8	1%
Paved		1.8	1.8	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.7	1.5	1.4	1.5	1.4	1.2	5%
Paved		1.8	1.8	1.8	1.8	1.8	1.7	1.8	1.7	1.7	1.7	1.6	1.5	1.5	1.4	1.3	10%

Figure 8. Peak flow of runoff as a function of SWMM catchment configuration.

Infiltration (in./yr)

Calibrated Low Medium High

Surface	Size (acres)	0.1			1			10			100			1,000			Slope
	Shape L/W	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	
Forest		22.1	22.3	22.4	22.4	22.5	22.7	22.6	22.8	22.9	22.9	23.0	23.1	23.1	23.1	23.2	1%
Forest		21.9	22.1	22.2	22.2	22.4	22.5	22.5	22.6	22.8	22.7	22.9	23.0	22.9	23.1	23.1	5%
Forest		21.8	22.0	22.1	22.1	22.3	22.4	22.4	22.5	22.7	22.6	22.8	22.9	22.9	23.0	23.1	10%
Grass		19.8	20.2	20.7	20.6	21.0	21.5	21.4	21.8	22.2	22.1	22.5	22.8	22.7	22.9	23.1	1%
Grass		19.4	19.8	20.2	20.0	20.5	21.0	20.8	21.3	21.8	21.6	22.0	22.4	22.3	22.6	22.9	5%
Grass		19.3	19.6	20.0	19.8	20.2	20.7	20.6	21.0	21.5	21.4	21.8	22.2	22.1	22.5	22.8	10%
Mixed		13.5	13.9	14.4	14.3	14.8	15.5	15.3	15.9	16.5	16.3	16.8	17.1	17.0	17.2	17.0	1%
Mixed		13.2	13.5	13.8	13.7	14.2	14.7	14.5	15.2	15.8	15.6	16.2	16.8	16.6	17.0	17.2	5%
Mixed		13.1	13.3	13.6	13.5	13.9	14.4	14.3	14.8	15.5	15.3	15.9	16.5	16.3	16.8	17.1	10%
Paved		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1%
Paved		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5%
Paved		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	10%

Figure 9. Average annual infiltration as a function of SWMM catchment configuration.

Technical Note 5

Catchment Configuration Sensitivity Analysis

Evaporation (in./yr)

Calibrated | Low | Medium | High

Surface	Size (acres)	0.1			1			10			100			1,000			Slope
	Shape L/W	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	
Surface	Forest	2.77	2.78	2.78	2.78	2.79	2.79	2.79	2.80	2.81	2.81	2.81	2.82	2.82	2.82	2.82	1%
	Forest	2.77	2.77	2.77	2.77	2.78	2.78	2.78	2.79	2.80	2.80	2.80	2.81	2.81	2.81	2.82	5%
	Forest	2.76	2.77	2.77	2.77	2.78	2.78	2.78	2.79	2.79	2.79	2.80	2.81	2.81	2.81	2.82	10%
	Grass	2.83	2.86	2.89	2.88	2.91	2.95	2.93	2.97	3.02	3.00	3.04	3.07	3.06	3.09	3.12	1%
	Grass	2.81	2.83	2.86	2.85	2.87	2.90	2.89	2.93	2.97	2.95	3.00	3.04	3.02	3.06	3.09	5%
	Grass	2.80	2.82	2.84	2.83	2.86	2.89	2.88	2.91	2.95	2.93	2.97	3.02	3.00	3.04	3.07	10%
	Mixed	4.9	5.0	5.2	5.1	5.3	5.6	5.5	5.8	6.2	6.0	6.5	7.1	6.9	7.6	8.4	1%
	Mixed	4.8	4.9	5.0	5.0	5.1	5.3	5.2	5.4	5.7	5.6	6.0	6.4	6.3	6.8	7.4	5%
	Mixed	4.8	4.9	5.0	4.9	5.0	5.2	5.1	5.3	5.6	5.5	5.8	6.2	6.0	6.5	7.1	10%
	Paved	6.8	7.0	7.2	7.1	7.4	7.8	7.7	8.2	8.8	8.6	9.4	10.4	10.0	11.2	12.5	1%
	Paved	6.7	6.8	6.9	6.9	7.1	7.4	7.3	7.6	8.1	7.9	8.5	9.2	8.9	9.9	11.0	5%
	Paved	6.7	6.7	6.9	6.8	7.0	7.2	7.1	7.4	7.8	7.7	8.2	8.8	8.6	9.4	10.4	10%

Figure 10. Average annual evaporation as a function of SWMM catchment configuration.

Sediment Load (ton/acre/yr)

Calibrated | Low | Medium | High

Surface	Size (acres)	0.1			1			10			100			1,000			Slope
	Shape L/W	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	0.25	1.0	4.0	
Surface	Forest	0.34	0.23	0.15	0.20	0.14	0.09	0.10	0.07	0.05	0.06	0.04	0.03	0.04	0.02	0.02	1%
	Forest	0.47	0.36	0.25	0.31	0.21	0.14	0.16	0.11	0.08	0.09	0.06	0.04	0.05	0.04	0.03	5%
	Forest	0.51	0.43	0.30	0.36	0.26	0.17	0.20	0.14	0.09	0.10	0.07	0.05	0.06	0.04	0.03	10%
	Grass	0.21	0.21	0.21	0.21	0.21	0.22	0.21	0.22	0.22	0.22	0.20	0.17	0.18	0.14	0.09	1%
	Grass	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.22	0.22	0.21	0.21	0.19	0.14	5%
	Grass	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.22	0.21	0.22	0.22	0.22	0.20	0.17	10%
	Mixed	0.18	0.15	0.11	0.12	0.10	0.08	0.08	0.06	0.05	0.05	0.04	0.03	0.04	0.03	0.03	1%
	Mixed	0.19	0.18	0.15	0.17	0.12	0.10	0.11	0.09	0.06	0.07	0.05	0.04	0.04	0.04	0.03	5%
	Mixed	0.18	0.19	0.17	0.18	0.15	0.11	0.12	0.10	0.08	0.08	0.06	0.05	0.05	0.04	0.03	10%
	Paved	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.31	0.34	0.27	0.21	0.23	0.17	0.12	1%
	Paved	0.38	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.39	0.35	0.28	0.30	0.24	0.18	5%
	Paved	0.37	0.39	0.40	0.40	0.40	0.40	0.40	0.39	0.39	0.39	0.39	0.31	0.34	0.27	0.21	10%

Figure 11. Average annual sediment load as a function of SWMM catchment configuration.

Technical Note 5

Catchment Configuration Sensitivity Analysis

The sensitivity analysis results demonstrate the interactive influences of four key factors associated with SWMM catchment configuration. A number of interesting trends were apparent in the results of the sensitivity analysis, some of which are listed below by indicator:

Runoff Volume

- For pervious surfaces, annual average runoff volume reduces by about one order of magnitude across five log-cycles of increasing catchment size.
- For impervious surfaces, volume decreases by about 20 to 30 percent across five log cycles of increasing catchment size (compared to 85 to 90 percent for pervious surfaces). For evenly mixed surfaces where impervious is routed to pervious, the reduction with increasing size is about 75 to 85 percent on an annual average basis.
- In general, higher slopes yielded more runoff than lower slopes for all surface types.
- For catchments having the same size and slope, those with shorter/wider flow paths yield higher runoff volumes than those with longer flow paths.

Peak Flow

- A strong diagonal gradient confirms that smaller impervious surfaces yield the highest peak flows, while larger pervious surfaces yield lowest peak flows. In fact, conventional stormwater infrastructure (storm drains, catch basins, etc.) essentially make large impervious areas behave like small catchments by minimizing the length of the runoff flow path.
- Slope has more of an influence on peak flow in larger impervious watersheds or smaller pervious watersheds. Peak flow is not as strongly affected by slope in smaller impervious watersheds or larger pervious watersheds.
- For catchments having the same size and slope, those with shorter/wider flow paths yield higher peak flows than those with longer flow paths.

Infiltration and Evaporation

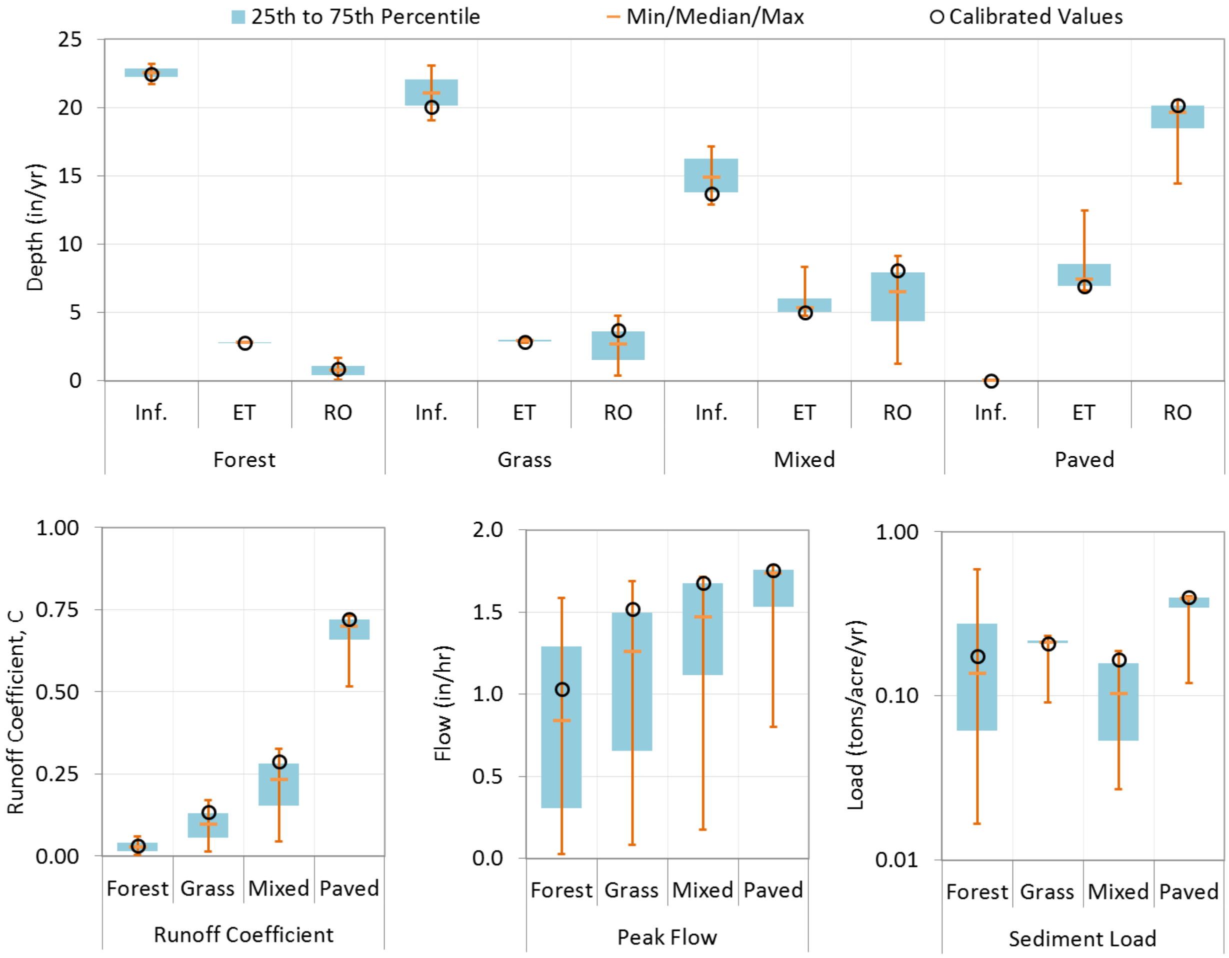
- In the same way that infiltration is unchanged (i.e. zero) for impervious surfaces, annual average evaporation volume remains constant for pervious watersheds, regardless of size or slope.
- For the annual water budget, infiltration compensates for evaporation on pervious surfaces, while evaporation compensates for the lack of infiltration on impervious surfaces.
- Impervious and mixed surfaces show both higher evaporation and lower infiltration with increasing slope.
- Annual evaporation volume from impervious and mixed surfaces approximately doubles across five log cycles of watershed size. Lower slopes provide more evaporation opportunity than higher sloped areas.
- Infiltration also increases across five log cycles of watershed size, but only by about 33 percent (compared to 100 percent for evaporation).
- For catchments having the same size and slope, those with longer flow paths yield higher infiltration and evaporation than those with shorter/wider flow paths.
- One counter-intuitive trend was observed for the largest and longest catchment size scenario. For the mixed surface case, infiltration increased from 1 percent slope to 5 percent, but then

decreased from 5 percent to 10 percent. This may be an artifact of the interplay of the increased infiltration and evaporation potential as parameterized for larger and longer catchment areas.

Sediment Load

- For catchments having the same size and surface cover, those with higher slopes and shorter/wider flow paths yielded more sediment load than those with lower slopes and longer flow paths.
- The smallest catchments yielded at least one order of magnitude more sediment per unit area than the larger catchments.
- Pervious catchments generate measurable sediment (in terms of tons/acre/year) for all sizes, as compared to impervious catchments. Pervious sediment load is generated using HSPF sediment erosion routines, while impervious sediment load is generated using SWMM build-up washoff functions.
- As parameterized, the smallest impervious catchments generate more sediment load than the smallest pervious catchments; inversely, the largest pervious catchments generate more sediment than the smallest impervious catchments.
- Among the largest catchments, the impervious surfaces yielded much less sediment than pervious surfaces of the same size, shape and slope, even though runoff volume and peak flow seemed to suggest it might have been otherwise. It appears that longer travel times may allow sediment to settle out during transport for larger watersheds. This suggests that the catchment size assumptions influence sediment yield more than predicted runoff volume or peak flow.

Ensemble statistics of the model results are presented in Figure 12, along with the values used for calibration purposes. Certain parameters, such as evapotranspiration, see little variance between sensitivity cases. For almost all cases, a more conservative value was chosen for runoff, peak flow and sediment load, within the distribution of the respective parameter.



Inf = infiltration; ET = evapotranspiration; RO= runoff

Figure 12. Ensemble statistics of SWMM results.

Technical Note 6

Pollutant 1st Order Decay Rate Sensitivity Analysis

First-order pollutant decay rates can be configured through calibration to provide an expected level of annual treatment; however, the actual percent removal will on an event basis will vary. If lieu of BMP inflow and outflow concentrations for calibration, the default loss rate of 0.01 hr^{-1} can be used.

While all structural BMPs considered in this analysis were assumed to have the same TSS decay rate, differences in infiltration rates, outlet configuration, and BMP geometry (static volume) also heavily influence the process of pollutant loss because the control fluid and pollutant residence time, or the time spent in the BMP before outflow. However, once residence time is established, the first-order decay rate controls how quickly a pollutant dissipates or is removed from the water column. This lumped parameter is meant to account for physical processes such as entrapment within soil media or settling out of the water column.

The first-order decay rates and background infiltration rates were then varied and TSS removal efficiency was assessed. The effect of decay rates on TSS removal for these two site-scale BMPs is shown in Figure 13 and Figure 14. Removal rates change by approximately 10 percent while decay rates vary across two orders of magnitude. The difference between the two curves in Figure 13 and Figure 14 is background infiltration losses which, unless a BMP in lined, tend to have the greatest impact on pollutant removal. With respect to the optimization, if all decay rates are held equal to one another, TSS reductions due to infiltration losses will drive optimization towards those BMPs with higher infiltration losses per unit cost.

Technical Note 6
Pollutant 1st Order Decay Rate Sensitivity Analysis

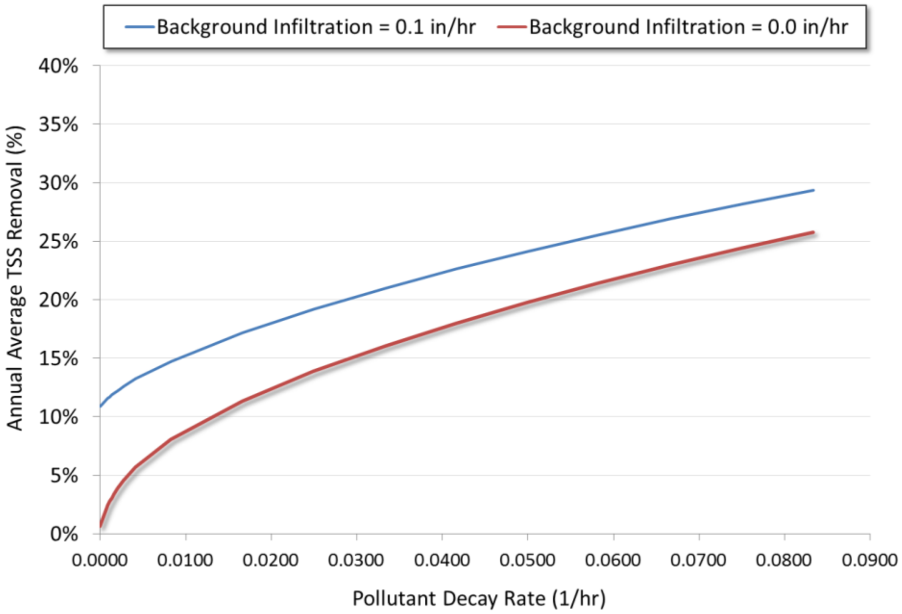


Figure 13. Comparison of TSS removal rate and decay rates within an example bioretention basin with two cases of saturated background infiltration rates.

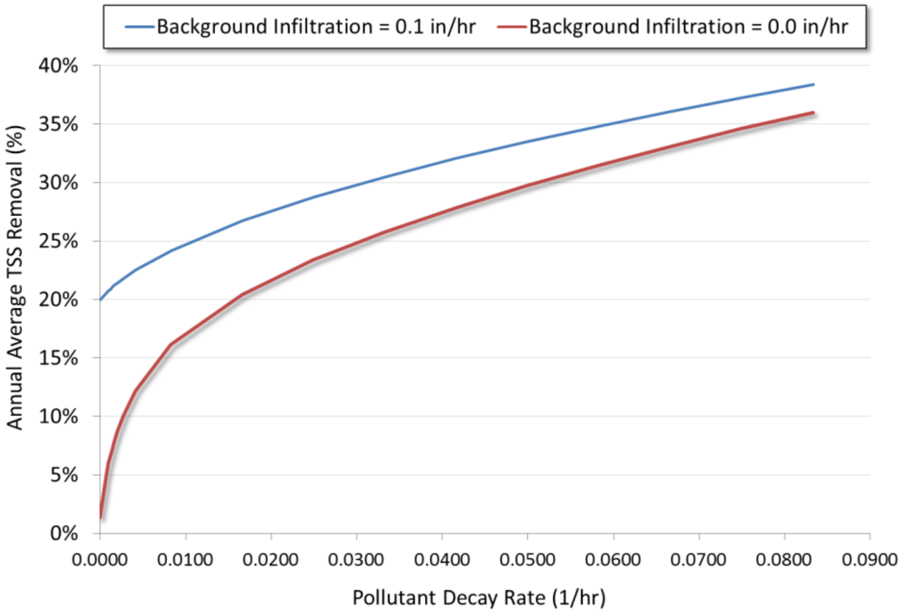


Figure 14. Comparison of TSS removal rate and decay rates within an example porous pavement unit with two cases of saturated background infiltration rates.

Technical Note 7

Solution to Using Both the Internal SWMM Engine and the Aggregate BMP

EPA *SUSTAIN* offers two operating modes for simulation: an external mode, where a locally calibrated watershed model (e.g. HSPF, P8) is used to generate unit-area timeseries of runoff and pollutant load, and an internal mode where simulations take place within the *SUSTAIN* interface. *SUSTAIN* contains an embedded version of SWMM 5.0.009 (*SUSTAIN* SWMM).

A modeler might choose to use the external simulation option in order to have more control over the modeling process. Unit-area timeseries generated for each land cover in these external simulations are used as boundary conditions to describe land covers in *SUSTAIN*, allowing for more computationally efficient optimization and control over runoff and pollutant loadings.

Perhaps more importantly, without the use of the external simulation model, *SUSTAIN* does not allow use of the aggregate BMP framework, limiting optimization routines to only existing BMPs. This is due to a fundamental difference between the internal and external simulation within *SUSTAIN*. The external simulation allows the modeler to assign loads per hydrologic response unit while the internal simulation assigns loads by catchment. Because catchment based loading does not have individual land covers like the external simulation, land covers cannot be assigned to the different BMPs within an aggregate BMP and optimization is thereby limited.

One solution that will enable the modeler to use both the internal *SUSTAIN* SWMM simulation and the aggregate BMP was used as part of the Duluth case study. *SUSTAIN* SWMM can be used to generate unit area catchments for each land cover. This timeseries is then used to build the SUSTAIN model using the external simulation option. This process allows the modeler to generate unique load timeseries for each land cover using SWMM, which can later be used as timeseries as an external simulation, so that the aggregate BMP can be used.

Technical Note 8

Transferring a SUSTAIN Project

There can be a need to transfer model files from one user to another. This need can present itself when sharing projects between stakeholders, transferring model products to a client, or simply when digital project files need to be moved or archived. In these cases it is important to remember that *SUSTAIN* is an integrated modeling framework. As with most software frameworks, special care must be taken to ensure that the project files (including all dependencies) are transferred completely and properly. Project dependencies include at a minimum all of the files listed in Table 3. In the event that a *SUSTAIN* input file(s) was modified directly in a text editor (see Technical Note 3), the modeler should be diligent in documenting what changes were made and why. Future users must be aware that changes made directly to an input file will not be reflected in the ArcGIS environment.

The following steps outline a suggested process for successfully transferring all *SUSTAIN* project files while maintaining the ability to launch the model using the ArcGIS interface. The first two steps should be skipped if *SUSTAIN* v1.2 has already been installed and activated. To transfer and launch an existing *SUSTAIN* ArcGIS project:

1. Install *SUSTAIN* v1.2 on your computer. Refer to the *EPA SUSTAIN (version 1.2) Installation Guide* included with your *SUSTAIN* installation executable for instructions.
2. Open any existing ArcGIS project and add the *SUSTAIN* toolbar as described in the *SUSTAIN Step-by-Step Application Guide* and save the project. Close ArcGIS. This will enable *SUSTAIN* functionality for *SUSTAIN* ArcGIS projects. It should be enabled before opening an existing *SUSTAIN* ArcGIS project. Note: *SUSTAIN* is only functional on ArcGIS 9.3.1 with Service Pack 2 and above.
3. Create a root file path that is identical to the file path used for the original *SUSTAIN* project (ex. C:\SUSTAIN\GIS\) and copy the model files provided to that location. This file path should be provided by the original modeler.
4. Update the file pathways in the following files (Note: the actual project name will precede the file extension ".src". "*SUSTAIN*" is used as a generic project name for the purposes of these instructions):
    a) SUSTIAN.src
    b) SUSTAIN_data.src
5. Launch the SUSTAIN.mxd ArcGIS map provided (Note: the actual project name will precede the file extension ".src". "SUSTAIN" is used as a generic project name for the purposes of these instructions).

When setting up a new *SUSTAIN* project there are some common practices that will facilitate this file transfer process including:

- Keeping all project files under a self-contained folder structure
- Adopting good file naming conventions that avoid the use of spaces and special characters
- Setting up the ArcGIS environment to use relative file paths in MXD files

Technical Note 8

Transferring a SUSTAIN Project

Table 3. *SUSTAIN* project files

File	Description	Comment
SUSTAIN.mxd	*SUSTAIN* GIS project	Store relative pathnames to data sources
SUSTAIN.src	Specifies file pathway for Project data folder, ET Option, Simulation Option, and names of land use grid, land use look up table, watershed grid, dem grid (not necessary), and stream grid (not necessary)	File pathways given in this file must be updated to the current location of the *SUSTAIN* project on the user's computer.
SUSTAIN_data.src	Specifies file pathways for cost databse, geodatabase, and project data folder	
Project Folder	Folder to which SUSTAIN related shapefiles and tables are saved	
Project.gdb	Project geodatabase	Can be used to organize GIS files, but must be done manually through the SUSTAIN->Data Management menu
basinroute1.shp	BMP SWS assignments shapefile	Used to determine BMP drainage area
bmp1.shp	BMP type locations shapefile	
conduits1.shp	BMP routing shapefile	
raster	SWS raster	Created by SUSTAIN when shapefile is specified
AgBMPDetail.dbf	Aggregate BMP design parameters	
AgLuDistribution.dbf	Aggregate BMP land use routing	
BMPDefaults.dbf	Default BMP design parameters	
BMPDetail.dbf	Aggregate BMP design parameters	Includes individual BMPs, junctions, and conduits
BMPNetwork.dbf	BMP routing	To-from definitions
BMPTypes.dbf	BMPs defined for the project	
Land use raster	Land use data for the study area	
LULOOKUP.dbf	Land use lookup table that links GIS land uses to land use time series	
OptimizationDetail.dbf	Optimization setup table	
Pollutants.dbf	Pollutants defined for the project	
TSAssigns.dbf	Impervious and sediment characteristics of time series land uses	

Provide file pathways to project data	Project data